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Perspectives of double skin façades for naturally ventilated buildings: A review

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ABSTRACT

This paper identifies the parameters affecting the thermal and energy performance of buildings with double skin façades (DSFs). It reviews the state of the art of current body of literature about the application of DSF technologies in order to provide guidelines to optimise such designs in naturally ventilated buildings. Three groups of parameters are identified as having significant impact on the DSF performance: the 'façade' parameters, which comprise the features of the cavity and the external layer of the façade; the 'building' parameters, which are those related to the physical configurations of the building; and the 'site' parameters, which are related to the effects of the outdoor environmental conditions on the building and the DSF behaviours. For each group of parameters, a comprehensive table is compiled summarizing the main findings of the studies that directly and indirectly contribute to the understanding and implementation of such technology. Guidelines established for the design of naturally ventilated buildings indicated potential application of DSF for improving the indoor thermal comfort even in warmer regions. However, further investigations expanding the analysis beyond the cavity are needed in order to evaluate the influence of the DSF on the thermal comfort in the user space.

Contents

Abbreviations: DSF, double skin façade; ACH, air change per hour; UAE, United Arabic Emirates; BES, building energy simulation; SC, shading coefficient; ETTV, envelope thermal transfer value (W/m²); CFD, computational fluid dynamics; WWR, window to wall ratio

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1. Introduction

The global consciousness about energy efficiency and sustainability in the construction sector has raised interest in the passive systems applied to buildings. A 'passive building' is one in which indoor environment is regulated not by the operation of mechanical heating and cooling systems but by the structure and architectural design of the building and its components [1]. The integration of passive design strategies are likely to occur at the conceptual design level, by determining the elements that have critical influence on building performance, such as its form and orientation, wall-window ratio, glazing type and shading, among others [2].

Among the passive solutions, the double skin façade (DSF) has recently become a popular technology. The motivation for using DSF comes from the desire to combine the transparent façade of modern buildings with energy efficiency. However, its implementation is accompanied by significant challenges due to the complexity of the thermal and airflow phenomena involved in its behaviour as well as the adaptability of these solutions to climatic conditions of different geographical regions [3,4].

According to Wong et al. [5] most of the studies about the DSF performance have been carried out in temperate climate conditions. However, the possibility of using the technology as means to introduce natural ventilation to buildings in the tropics has been suggested [6–8]. Nevertheless, guidelines or recommendations for modelling DSFs are still in the early stages of development, especially in hot and humid climate. Therefore, further research is required for a better understanding of the processes involved in DFS and the implication of its use in different climates [9,11].

In the present paper the parameters influencing the performance of buildings with DSF are identified. The aim of this study is to review the body of literature from the last decade on studies about experimental and computational simulation of DSFs to draw conclusions about their implementation in naturally ventilated buildings.

2. Concept and functionality of the double skin façade

The concept of DSF was introduced in early 1900s, but little progress was made until the 1990s [12]. The history of DSF is not particularly established and knowledge on the physical processes involved is still lacking. Although its use is more popular in places with more stringent building energy performance regulations, most countries do not have any standard guidelines on how to design and assess the performance of DSF, which can be a barrier for its implementation [11,13].

A DSF consists of a normal façade, an air cavity and an additional external skin usually made of glass. It is a common practice to implement a shading system within the cavity between the two layers of the façade. To De Gracia et al. [14] the main factors that encourage air movement in buildings with DSF are the movement of the surrounding wind and the pressure difference due to the thermal buoyancy that occurs in the cavity. The phenomenon of thermal chimney within the DSF occurs due to the density difference between the warmer air inside the cavity and the cooler air outside. The air inside the cavity is warmed up by the solar radiation and exhausted to outside from the top of the cavity. In naturally ventilated building, fresh air is often drawn from windows on the opposite side of the DSF, which passes through the occupant space before being extracted into the cavity of the DSF [15,6].

One of the advantages of DSF is the promotion of the natural ventilation which provides good indoor air quality and improves thermal comfort without any electricity demand [16,17]. However, the design of DSF for naturally ventilated buildings is delicate due to the interaction of thermal processes and the airflow mechanisms, which depend on the properties of various components of the façade structure and the building itself [18,19]. Therefore, predicting the performance of a DSF is not a trivial exercise and its application requires even more considerations when it is applied to naturally ventilated buildings.

Different aspects of the DSF have been reviewed presenting the advances in its design [10,20,21], the availability of computational models [14] and the existing research methods used to study its performance [22]. Additionally, a number of studies have been undertaken and reported on the behaviours of DSF over heating and cooling seasons [23,8,24]. On the other hand, some studies focused on specific aspects, which are outside the scope of this study, such as daylighting [25,26], smoke escape [27,28], photovoltaic applications [29,30], condensation [31] and the effect of plants within the cavity [32].

In spite of the potential positive effects of implementing the DSF, there are some concerns about its application such as: the costs for its design, construction and maintenance, which are considerably higher than a traditional single façade [21,33]; the increase of the weight of the structure; the sound transmission from room to room or floor to floor through the cavity; the fire regulations and the reduction of useful office space [34].

3. Façade design parameters

This section summarises the influence of the DSF components on the building performance such as cavity depth, position and type of shading devices, glazing materials, structure of the façade as well as the size of the cavity openings. The decisions about the façade design have an impact on several aspects of the building like its thermal characteristics, ventilation strategy and shading control [10].

3.1. Cavity depth

When properly designed, the cavity has the potential to significantly reduce the building energy consumption. However, a poorly designed cavity can result in uncomfortable indoor temperatures and additional energy consumptions [35]. One of the factors most studied about the cavity in DSFs is its depth, which may vary from 10 cm to more than 2 m according to different design concept such as the provision of enough space for the shading device, an adequate access to the cavity interior for maintenance and cleaning [36].

Evaluations of DSF's cavity depth on the amount of solar heat transferred through the cavity and the resulting temperature and ventilation rates produced have been evaluated by Rahmani et al. [37], Torres et al. [34] and Radhi et al. [15]. The results show that narrower cavities presented an accentuated stack effect and a stronger air movement which leads to a more effective extraction of the warmer air through the cavity. On the other hand, in larger cavity depths (more than 1 m) there is a reduction in the stack effect and the heat transfer towards the interior rooms increases. Thus, a cavity depth between 0.7 and 1.2 m was recommended by Radhi et al. [15] as it made a balance between air extraction and heat transmission to the user room.

In air-conditioned buildings the accentuated stack effect in the cavity resulted in less energy demand for cooling the building and thus, narrower cavities were preferred. However, in a naturally ventilated building the influence of the cavity airflow on the interior of the building still needs investigation due to the proximity of these openings to the user room. Similarly, the equilibrium between the ventilation rate to remove heat from the

indoor space and the heat transfer from the cavity to the room still needs to be addressed.

3.2. Shading device

One reason for implementing DSF is the possibility of positioning a shading device within the cavity because it reduces maintenance costs. Currently, there are many shading device options available: roller shades, louvered blinds, fixed and manually or automatically controlled. They can regulate the solar incidence reaching the internal layer and enhance the airflow through the building. As a consequence, it keeps the room cooler and improves the thermal comfort in warmer conditions [8,36].

The position of the shading device within the cavity was examined by Gratia and De Herde [38] and Jiru et al. [39]. Three different case scenarios were simulated: (i) device close to the inner layer; (ii) device close to the outer layer; and (iii) device in the middle of the cavity (Fig. 1a). The results showed that the temperature of the inner glass surface becomes higher when the systems were positioned close to it. This led to higher heat transfer from the cavity to indoor and consequently higher cooling loads in the user room. However, when the blinds were placed in the middle of the cavity, the thermo circulation was well established with air flowing on both sides of the blinds.

The influence of different blind's angles (0°, 30°, 45°, 60° and 80°) on the convective, conductive and radiative heat transfers through the DSF system was investigated by Ji et al. [40] (Fig. 1b). It was observed that the presence of venetian blinds not only offered the shading function but also enhanced the natural ventilation in the cavity. Turbulent airflow around the heat absorbing blind slats forms a large upwards buoyancy momentum, which drives the air out of the cavity through its top. In this study, the buoyancy effect enhanced the natural ventilation in the cavity up to 35%, when blind's angle was 80°.

Simulations comparing the effect of colour (white and black) of the material used on the shading device were performed by Haase et al. [41]. The results showed that the cavity with black roller blind presented an air temperature 11 °C higher than with the white blind. Application of different shading coefficients (SC) were conducted by Chou et al. [42]. SC refers to an indicator of how the glazing shades the interior when there is direct sunlight on the pane. It was observed that the heat transfer through the DSF varied from a low (18 W/m^2) to a high value (59 W/m^2), corresponding to the range of SC from 0.3 to 0.7, respectively.

In conclusion, the shading device increases the air temperature inside the cavity especially if they are made of dark colour materials. The decision about the location of the blinds has considerable influence on the air temperature and on the ventilation rate. Placing the shading device in the middle of the cavity allows for air circulation on both sides but if placed close to the inner layer, higher heat transfer towards the internal environment may occur. Regarding the angle of the blind, it was suggested that horizontal angles acted as an obstruction to the air circulation; therefore, higher angles seem to be more appropriate.

3.3. Outer skin glazing properties

According to Pérez-Grande et al. [43] the understanding about the solar radiation transmission through the façade layers, the surface view-factors, the airflow regimes and the vertical temperature gradient are very important in the prediction of the façade performance. When the solar radiation reaches the external skin, it is either reflected, absorbed or transmitted. The solar radiation that passes through the outer glazing is absorbed by the inner layer which warms up and causes emission of long wave radiation in all directions. Most of this radiation arrives on the external skin and is reflected or absorbed. Thus a significant portion of solar radiation is trapped in the cavity and consequently increases the air cavity temperature [43,44]. Fig. 2 presented by Høseggen et al. [9], illustrates in detail the complexity of heat transfer mechanisms and airflow paths involved in the DSF.

When considering the influence of different glazing properties on the heat transfer, a low transmittance and high absorptance glazing applied on the external glazing combined with low

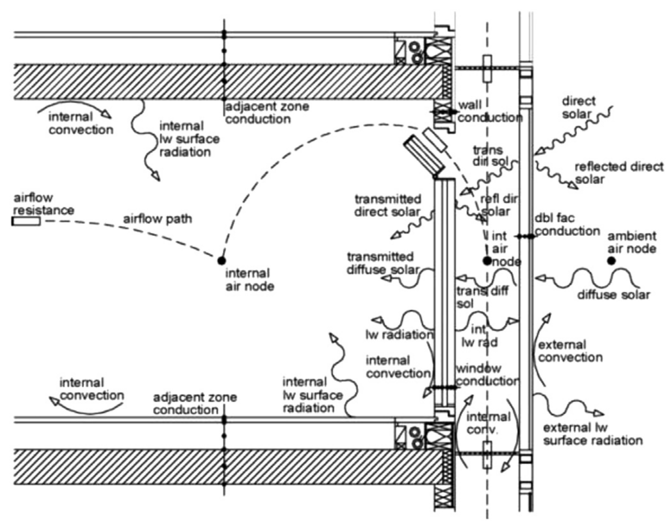

Fig. 2. DSF and the adjacent office floor cross-section with the heat transfer mechanisms and the airflow network illustrated by Høseggen et al. [9].

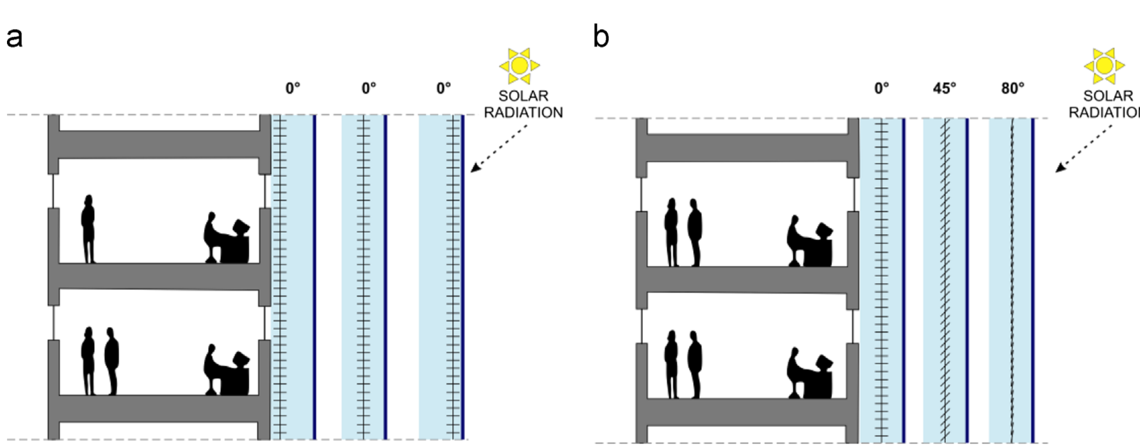

Fig. 1. Variations of the shading device (a) position proposed by Gratia and De Herde [38] and (b) angle evaluate by Ji et al. [40].

emissivity glazing internal pane can lead to a reduction in solar heat gain to the occupied space. In this case, most part of the heat is blocked before reaching the cavity [19]. However, the application of a high-absorbing inner material in conjunction with an equal transmittance/absorptance glazing of 0.4 on the outer layer results in the highest air mass flow rate passing through the cavity as studied by Pérez-Grande et al. [43] and presented in Table 1.

It is a common practice to use double glazing as the inner layer and single glazing on the outer skin of DSFs. In air conditioned buildings the double glazing minimises both the convective and the radiative components of heat transfer thus reduces the cooling load inside the building [45]. Nevertheless, one of the case scenarios tested by Chan et al. [46] used single glazing on the inner layer and double glazing on the outer skin (Fig. 3). Despite of the difference in glazing properties applied to the cases (b) and (d), the resulted energy consumption of both cases were relatively close. It showed that the better thermal insulation property of the double glazing as the outer pane of the DSF was effective in reducing the heat gain through the cavity and then into the building.

However, in naturally ventilated buildings it is important to achieve higher airflow in the cavity by increasing its air temperature. The application of a glazing with higher transmittance on the outer layer (single glazing instead of double glazing) tends to pronounce this behaviour. On the other hand, double glazing with higher thermal insulation is likely to be applied at the inner layer of the façade in order to reduce the radiative and conductive components of heat transfer across the façade. A suitable combination of glazing type is necessary to achieve a balance between the stack effect in the cavity and the heat transfer to the user room.

Table 1
DSF performance according to the glazing characteristics by Pérez-Grande et al. [43].

		Reflectance	Transmittance	Absorptance
Lowest heat rate into the building	Outer layer	0.1	0.1	0.8
	Inner layer	0.2	0.4	0.4
Highest mass airflow rate passing through the cavity	Outer layer	0.2	0.4	0.4
	Inner layer	0.1	0.1	0.8

3.4. Structure

Oesterle et al. [33] proposed a classification of the DSF according to the structure of the system or to the form in which the intermediated space is divided (Fig. 4). The four types identified are:

(a) The box window type which has the cavity between the two layers divided horizontally and vertically along the constructional axes, on a room-by-room or on an individual window element basis. In this case, the windows on the inner layer can be operable to allow for natural ventilation.
(b) The shaft-box is a special form of box window type in which the continuous boxes form a vertical shaft that extends over a

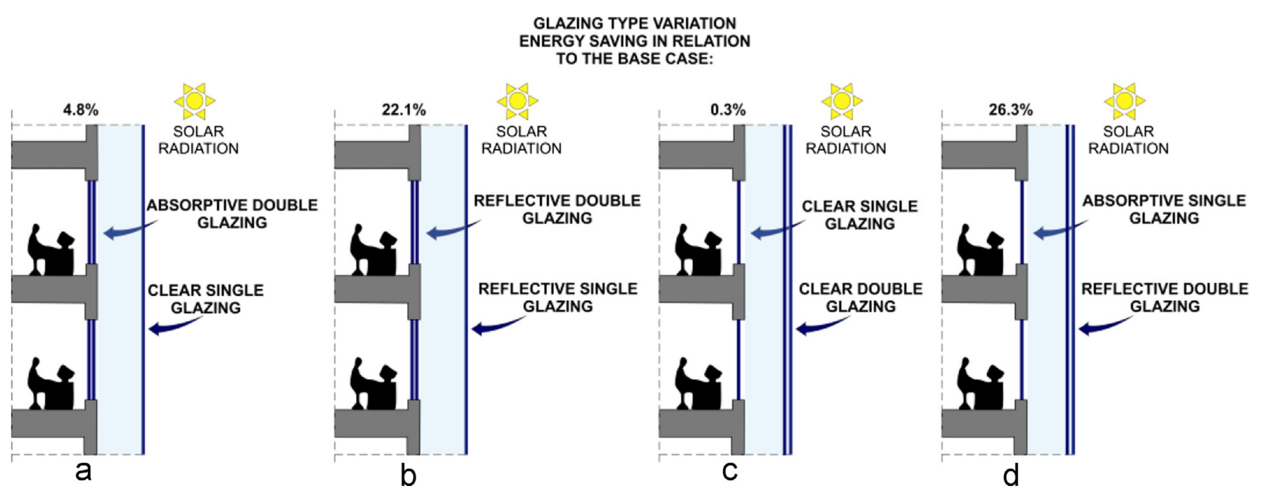

Fig. 3. Performance of a building with DSF under variations of the glazing properties resulted from Chan et al. [43].

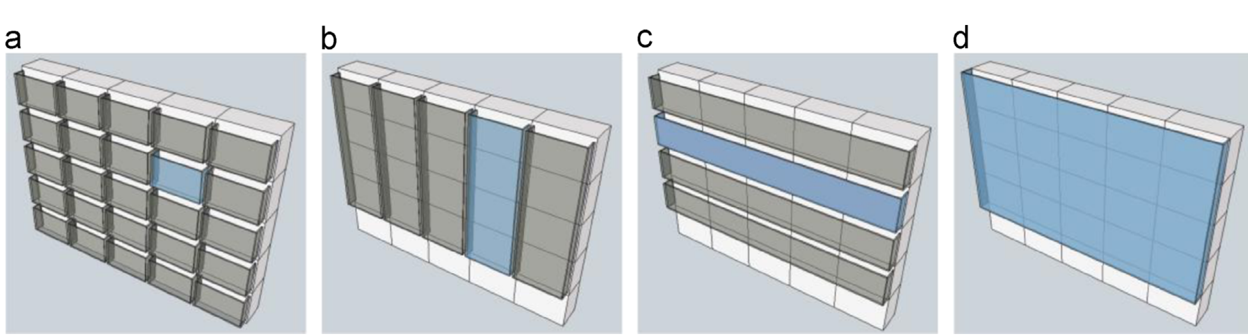

Fig. 4. DSF classification: (a) Box Window, (b) Shaft-Box, (c) Corridor and (d) Multi-Storey double skin façade.

Table 2
Summary of research on 'façade' parameters and key findings.

Parameter	Author/year	Location	Variation	Tool	Type of ventilation	Major findings/Observations
Cavity depth	Rahmani et al. [37]/2012	Johor Bahru, Malaysia.	30, 50, 100 and 150 cm	Flovent (CFD)	Air conditioned	• Increasing the cavity size up to one meter reduces solar heat gains in the building, but for lager cavities, the DSF has its efficiency reduced.
	Radhi et al. [15]/2013	Al-Ain city,UAE.	50, 70, 100, 120, 150 cm	Design-Builder (BES) + PHONICES-FLAIR (CFD)	Air conditioned	• Heat transfer rates decrease when the cavity depth is reduced due to the higher ventilation rates. • Cavity size between 0.7 and 1.2 m can give a balance between solar gain and heat transmission.
	Torres et al. [34]/2007	Barcelona, Spain.	40, 60, 80, 100 cm	TAS (BES)	Air conditioned	• Narrow cavity with no horizontal partitions may demands less energy consumption due to accentuated stack effect occurring in the cavity.
	Gratia and De Herde [44]/2007	Uccle, Belgium.	30, 60 120, 240 cm	TAS (BES)	Air conditioned	• Temperature in deeper cavities is slightly lower than temperature in lower depth DSF.
Shading device	Gratia and De Herde [38]/2007	Uccle, Belgium.	position in cavity: close to the inner layer, to the outer layer and in the middle	TAS (BES)	Air conditioned	• When blinds placed in the middle of the cavity the movement of thermo circulation is well established and the cooling consumption is decreased.
	Jiru et al. [39]/2011	Torino, Italy.	slat angle: 0°,45°,90° position of the blind in the cavity: outer, middle, inner, no blind	Ansys Fluent (CFD)	Air conditioned	• The surface heat transfer coefficient for the angle = 90° (totally vertical) is lower than angle 45° and 0°(totally horizontal) cases. • The inner position lead to a high temperature on the inner glass surface, reducing the heat transfer from the indoors.
	Ji et al. [40]/2007	Lab experiment	Angles (0, 30, 45, 60, 80 degrees)	Ansys CFX (CFD)	–	• The presence of venetian blinds not only offers the shading function but also enhances the natural ventilation of the façade cavity. • The shading device has lead up to 35% enhancement in natural ventilation flow for the façade cavity and 75% reduction in heat loads for the internal environment.
	Haase et al. [41]/2009	Hong Kong, China.	Roller blind colour: black, white	TRNSYS and TRNFLOW (coupled with COMIS)	Air conditioned	• The black roller blind is largely responsible for high gap temperatures. A white coloured roller blind reduces gap temperatures by 11 °C.
	Chou et al. [42]/2009	Singapore	Shading coefficient (SC): 0.3, 0.4, 0.5, 0.6, 0.7	Experimental laboratory measurements	Air conditioned	• With the SC regulated from 0.3 to 0.7, the envelope thermal transfer values climb from a low value of 18 W/m^2 to a high of 59.6 W/m^2.
Outer skin glazing properties	Manz et al. [48]/2004	Duebendorf, Switzerland.	Glazing thermal properties (emissivity, thermal conductivity)	Laboratory	–	• The solar energy absorbed in the DSF is removed efficiently due to the mechanical ventilation. • A further decrease in total solar energy transmission would be possible, e.g. by increasing the outside solar reflectance of the shading screen.
	Guardo et al. [19]/2009	Barcelona, Spain.	Glazing transmissivity (from 35 to 78%) and emissivity (from 0.05 to 0.89)	CFD	Air conditioned	• Replacing the internal glazing for a low-emissivity glass can duplicate the reduction on solar load gain. • A reduction of external glazing transmissivity in 55% can lead to a 40% enhancement on the reduction in solar load gain.
	Pérez-Grande et al. [43]/2005	Not specified	Gazing properties and combinations	FLUENT (CFD)	–	• Highest mass airflow rate was obtained when the outer layer presents reflectance: 0.2; transmittance; 0.4 and absorptance: 0.4 and the inner layer has reflectance: 0.1; transmittance; 0.1 and absorptance: 0.8.
	Gratia and De Herde [44]/2007	Uccle, Belgium.	Material: reflective, clear, absorbing	TAS (BES)	Air conditioned	• Null wind speed. Clear glazing transmits most of the solar radiation (62%) and the reflective glazing returns 51% of it. • If the inner skin is absorbing glazing, most of the solar radiation (68%) which strikes the glazing is absorbed.
	Mingotti et al. [45]/2013	Cold and warm climates.	Single and double glazing	Analytical model	Air conditioned	• In warm climates double glazing minimises both the convective and the radiative components of heat transfer across the façade, leading to a smaller heat gain from the exterior ambient into the room connected to the façade.
	Chan et al. [46]/2009	Hong Kong, China.	Glazing positions: single and double	EnergyPlus (BES)	Air conditioned	• Inner layer made of single clear glass + outer layer made of low transmissivity double glazing can give decrease the heat gain and the building cooling energy.
Structure	Torres et al. [34]/2007	Barcelona, Spain.	corridor and multi-storey types	TAS (BES)	Air conditioned	• Due to cavity height, there is a sharper temperature gradient occurring along it. • The stack effect of multi-story and shaft types will be more accentuated, increasing its ventilation rate.
	Hong et al. [47]/2013	Seoul, South Korea	Box, corridor, multi-storey and shaft types	Design Builder (BES)	Air conditioned	• The multi-storey type had the lowest energy consumption. • The natural ventilation created was able to prevent the rise in temperature due to the solar heat gains.
Openings	Safer et al. [49]/2005	Not specified	Length of the inlet and outlet openings	Fluent (CFD)	Mechanical ventilated cavity	• Only the cavity was modelled. • The air path does not have influence on the air velocity in the cavity, while the openings areas are important factors to be considered
	Torres et al. [34]/2007	Barcelona, Spain.	Top and bottom of cavity dimensions: 5, 10, 15%	TAS (BES)	Air conditioned	• Larger openings help to extract warm air from the cavity as higher air flow rates occur.
	Gratia and De Herde [44]/2007	Uccle, Belgium.	Top and bottom of cavity dimensions: 2.5, 5, 7.5, 10cm	TAS (BES)	Air conditioned	• Cavity temperature decrease does not vary in a linear way with the size of the openings.

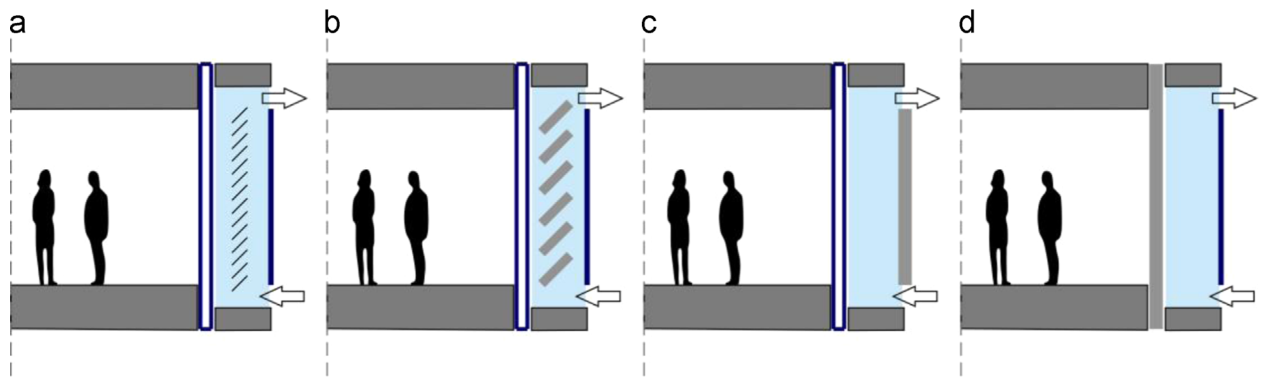

Fig. 5. Models using thermal mass (concrete) proposed by Fallahi et al. [51]: (a) conventional DSF with inner layer made of double glazing, outer layer set as single glazing and aluminium venetian blind; (b) aluminium blind replaced by a concrete blind; (c) outer layer replaced by concrete; (d) inner layer replaced by concrete pane.

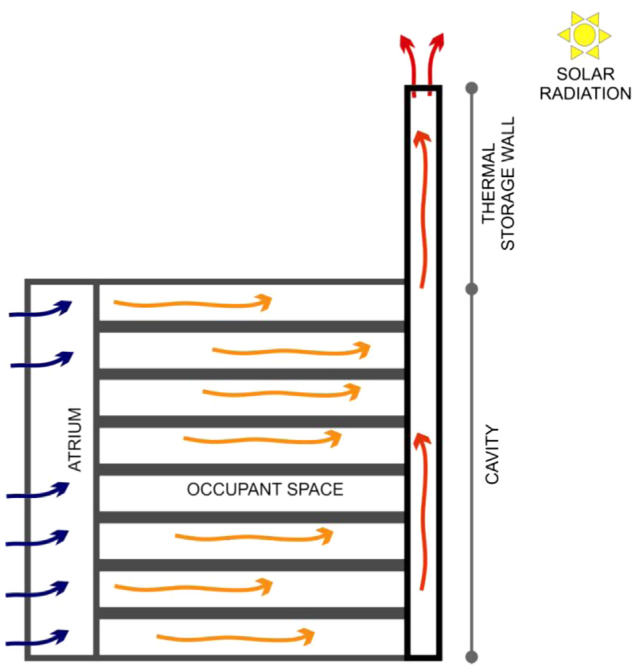

Fig. 6. DSF with thermal storage space above the cavity proposed by Ding et al. [6].

number of stories to create the stack effect. The typology requires fewer openings in the external skin and it influences positively in terms of insulation against external noise.

(c) The corridor type closes the intermediate space between the two skins at the level of each floor and divisions are expected along the horizontal length. The air-intake and extract openings in the external façade layer should be situated near the floor and the ceiling. In this case, special care should be taken to avoid sound transmission from room to room. The exhaust air from one room should be avoided to enter in the room above.

(d) The multi-storey style has the cavity adjoined vertically and horizontally by a number of rooms or extended over the entire building. The ventilation of the cavity occurs via large openings near the ground floor and the roof. This typology is suitable where external noise levels are very high. Oesterle at el. [33] suggest that some rooms behind the multi storey façade have to be mechanically ventilated.

Comparing the four types of DSF structure, the multi-storey type presented the greatest temperature gradient along the cavity due to its height. The pronounced stack effect on this DSF type accentuates the exit of the captured warm air from the top of the cavity, increasing its ventilation rate and resulting in a lower temperature inside the cavity and consequently reducing heat gain inside the room [34,47].

As the height of the façade is crucial to the DSF performance due to the optimisation of the buoyancy effect, the shaft-box and multi-storey types presents suitability for naturally ventilated buildings. These cases can prevent the rise in temperature inside the building or remove internal heat by introducing cooler outdoor air ventilation across the floor space. On the other hand, in the box-window and corridor cases the height difference between the air-inlet and air-outlet openings is smaller, covering only one floor. Thus, the DSF would not be so effective in promote natural ventilation.

3.5. *Cavity openings*

The cavity's openings are one of the main parameters affecting the performance of the DSF. It can influence the air temperature within the cavity, the buoyancy force and the flow resistance. An inter-relationship between the openings dimensions, air temperature and airflow rate were observed by Gratia and De Herde [44] and Torres et al. [34]. They observed that cavities with larger openings presented lower temperatures with higher airflow rate than cavities with smaller openings. Therefore, an optimum opening size is dependent on the outdoor conditions as well as on other characteristics of the DSF and the geometry of its structural elements.

In conclusion, the DSF performance is highly dependent on the geometry of the façade due to the physics of heat transfer processes occurring inside the cavity. The airflow path, the air velocity and the air temperature change along the height of the cavity, which are affected by a number of parameters such as the shading device configurations, the cavity width and glazing properties. Incorporating all these within the chosen DSF structure and the optimised opening settings are the key factors that will determine the effectiveness of the DSF in improving the indoor thermal comfort. Table 2 grouped the parameters evaluated in this section and summaries main findings of each study reviewed. The table also presents the location/climate and the tool used in each study, including the type of ventilation applied to the model. Although most of these 'façade' studies used air-conditioned models, many of their findings are directly relevant in informing the study of DSF in naturally ventilated buildings.

4. Building parameters

This section reviews studies on the impact of the key building parameters on the DSF thermal performance, which encompass the height of the building, the properties of the materials and the position and the size of the openings on the inner layer of the DSF.

Table 3
Summary of research on 'building' parameters and key findings.

Parameter	Author/year	Location	Variation	Tool	Type of ventilation	Major findings/Observations
Inner skin materials	Yılmaz and Çetintaş [50]/2005	Istanbul, Turkey	Single and double skin	calculation method	Naturally ventilated	• The inner glazing had higher temperature when compared to a transparent window of a single skin model.
	Fallahi et al. [51]/2012	Munich, Germany	Concrete applied to the blind, to the inner and to outer layer	BES	Cavity naturally and mechanically ventilated	• The application of the thermal mass on the shading device presented 27% of energy saving compared to the conventional case in which the blinds were made of aluminium.
	Radhi et al. [15]/2013	Al-Ain city, UAE	Material: single, double, triple glazing	Design-Builder (BES) + PHONICES-FLAIR (CFD)	Air conditioned	• The optical properties of the layers are the most effective way to reduce cooling loads, with a particular influence the direct gain and stack effects.
Wall-window ratio and openings	Haase et al. [41]/2009	Hong Kong, China	63, 91, 32	TRNSYS and TRNFLOW (coupled with COMIS)	Air conditioned. Mechanically ventilated cavity	• The WWR and glazing type have the greater influence on annual cooling load. DSF system with large internal window area (WWR = 0.91) has the same annual cooling load as the single skin façade system with small window area (WWR = 0.32).
	Ding et al. [6]/2005	Tokyo, Japan	Opening area of the inner layer: 1, 2 and 4 m^2	Experimental laboratory measurements + CFD	Naturally ventilated model	• Opening areas of $2m^2$ between the occupant space and the cavity was considered reasonable to obtain preferable ventilation performance.
	Chou et al. [42]/2009	Singapore	30, 50, 70, 90	Experimental laboratory measurements	Air conditioned	• For WWR = 50% and 70%, a reduction in the thermal transfer through the façade was observed. But for a WWR = 90%, the thermal transfer increased.
	Manz et al. [48]/2004	Duebendorf Switzerland	Opening at the top and bottom of the inner layer	Experimental laboratory measurements	Mechanically ventilated cavity	• The opening at the bottom of the inner layer leads to a low solar heat gain in the user room.
Height of the cavity/ Number of floors	Pappas and Zhai [36]/2008	Brussels, Belgium	3.0 m (one story) and 15.0 m (five stories)	EnergyPlus (BES) + PHONICES (CFD)	–	• A taller cavity will produce a stronger buoyancy force, creating a greater airflow rate.
	Radhi et al. [15]/2013	Al-Ain city, UAE	Monitoring points: 2.2, 6.2, 10.2 m	Design-Builder (BES) + PHONICES-FLAIR (CFD)	Air conditioned	• A small variation of temperature occurs at different heights, especially in the afternoon where the outside temperature is high. This increase is due to the higher rate of air flow into the cavity from each floor.
	Ding et al. [6]/2005	Tokyo, Japan	Height of the chimney above the cavity: 3.75, 7.5, 11.25m	Experimental laboratory measurements + CFD	Naturally ventilated	• The ACH rate does not change radically with the height of the chimney above the cavity. Recommendation: the solar chimney above the cavity should be more than two-floor high.

4.1. Inner skin materials

One of the parameters that influence the thermal behaviour of a building with DSF is the properties of the materials selected for the DSF layers. One common option for the inner layer is to use materials with high thermal mass. Discussions about the application of combined concrete and glazed windows on the inner layer by Yılmaz and Çetintaş [48] and Radhi et al. [15] indicate that the solar incidence on the glazing surfaces can achieve higher temperatures than the concrete. In warm climate conditions, increasing the amount of thermal mass can result in a decrease in the cooling loads of the building [48,15]. The study (Fig. 5) conducted by Fallahi et al. [49] showed that the application of thermal mass (concrete) on the shading device (b) and on the external layer (c) presented similar cooling requirements in the summer and less than the amount consumed in the conventional case (a). But the case in which the thermal mass was applied on the internal layer (d) had the highest cooling load.

Concrete has high thermal mass, thus its use in conjunction with the DSF provides "inertia" against temperature fluctuations. Although most studies used mechanical ventilation models, the underpinning principles of the application of thermal mass to alleviate the peak load and temperature in naturally ventilated buildings with DSF still apply. But the inter-relationship and performance of the thermal mass applications with variations in glazing areas and ventilation will need future investigations.

4.2. Wall-window ratio and openings

Windows provide beneficial daylight, direct sunlight and visual contact with the outside, but it may cause problems if excessive undesired heat gain occurs due to its high *U*-value, glare or asymmetric thermal radiation resulting in thermal discomfort. However, the addition of a second outer glazing skin on the building façade seems to be able to be more effective in addressing these problems [50].

The effect of the wall-window ratio (WWR) on the solar radiation gain component of the thermal transfer value (ETTV) through the DSF was evaluated by Chou et al. [42] and Manz et al. [51]. They observed that the positive influence to the energy consumption of employing a fenestration to reduce the solar heat gain into the building seems to be mitigated with a high WWR. Therefore, a balanced WWR is essential to reduce the heat transfer into the building. Chou et al. [42] observed a reduction in the overall annual heat transfer for the building located in Singapore when the WWR increased from 0.5 to 0.7; while an increase was obtained for the model with WWR of 0.9. Haase et al. [41] complemented that in terms of energy consumption, the building model tested presented annual savings of 26.4% for WWR of 0.32, when compared to the case WWR of 0.91, which was attributed to the amount of heat gain through the building envelope.

Ventilation performance of a naturally ventilated model with the façade area of 11.25 m by 3.25 m in each floor was studied by Ding et al. [6] who found around 7 ACH on the first floor when the fenestration had an opening area of 1 m^2 and 10 ACH for a 2 m^2 window. However, for 4 m^2 openings, this value only slightly increased to approximately 11 ACH. They concluded that an opening area of 2 m^2 between the occupant space and the cavity space was considered reasonable for ventilation purpose.

The studies reviewed show that there is a positive influence of high WWR on the inner layer of the DSF as it allows for higher airflow through the user rooms, removing part of the heat gains. However, disadvantages were observed with a high WWR due to the increase in solar gain, thus a balanced WWR threshold should be identified considering the building's design features and the local climatic conditions.

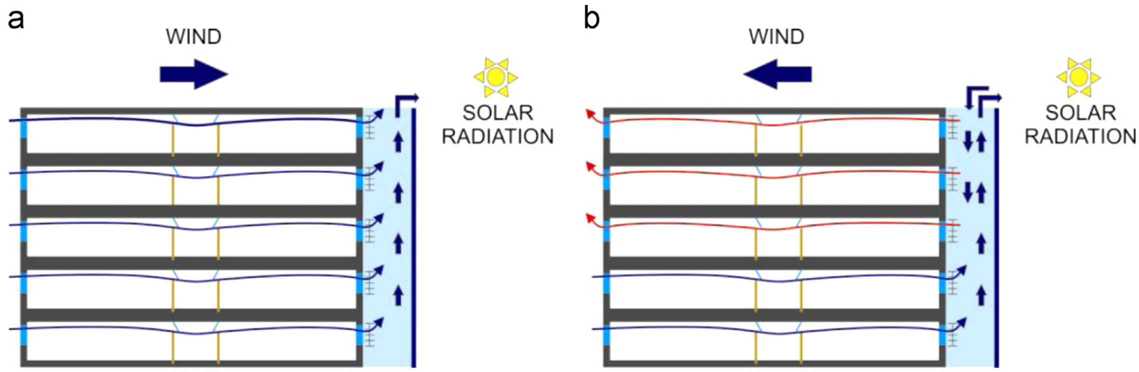

Fig. 7. DSF performance according to the wind orientation in relation to the façade according to the study of Gratia and De Herde [55].

4.3. Height of the cavity/number of floors

One of the main factors that affect the magnitude of the thermal buoyancy in DSFs is the height difference between the inlet and the outlet openings of the cavity, such that a taller cavity produces a stronger buoyancy force, creating a greater airflow rate. In cold seasons the cavity is heated by the solar radiation captured while during the warmer seasons it can be effective in extracting the excessive heat from the cavity and the user rooms [33,8].

The influence of the cavity height on the performance of a naturally ventilated model was evaluated by Ding et al. [6]. The model proposed has a cavity with a “thermal storage wall” which extends above the building (Fig. 6). The results show that increasing the height of the thermal storage space increases pressure difference between the top and the bottom of the cavity resulting in higher air change rate in each floor, especially in the upper floors. From the point of view of pressure difference, it is recommended that the thermal storage wall should be more than two-floor height, without which natural ventilation promoted by the DSF for the upper floors will not be enough to meet the thermal comfort without the use of mechanical systems.

Table 3 presents a summary of the key ‘building’ parameters and the main findings of each study reviewed.

5. Site parameters

This section presents studies on the key external parameters of surrounding site: level of local solar incidence, facade orientation, external temperature and wind conditions [21], that have significant impact to the thermal performance of the DSF and the building.

5.1. Solar irradiance and orientation

The temperature difference between the outside air and cavity air has been identified by Gratia and De Herde [44] and Kim et al. [52] as one of the most important factors in generating ventilation in a building with DSF. Not only it is directly proportional to the solar radiation level, to the glazing percentage and solar factor of the external layer, but it is also a function of the orientation and the solar shading generated by the surrounding environment and the building itself.

Studies by Stec and Paassen [4], Gratia and De Herde [44] and Kim et al. [52] on the effect of different levels of solar radiation to the cavity indicated that in sunny days the temperatures in the cavity of a south facing DSF (in the north hemisphere) exceeded the surrounding air temperature by around 20 °C when there was no shading device in the system. However, under cloudy sky conditions, the DSF functioned less effectively with maximum temperature difference of only 10 °C.

Regarding the orientation, Hamza [53] and Gratia and De Herde [44] agreed that the most unfavourable orientations for DSF were east and west as they increased the building's cooling loads. If the DSF was east oriented, overheating appeared early in the morning while for west orientation largest cooling was required at the end of the day. To Haase et al. [41] S, SE, and SW orientations are the most efficient positions for the DSF. They also recommended that in highly dense cities the shading created by surrounding buildings has to be considered.

Furthermore, Kim et al. [52] suggested that for a naturally ventilated building the east-facing DSF did not function beneficially in practice, while the west-facing skin received enough solar radiation and succeeded in generating ventilation for the indoor space. Thus, based on the studies on naturally ventilated buildings localised in north latitudes, the south facing (with 45° variations) seems to be most effective orientation to buildings with DSF. However, attention should be paid to the obstructions of neighbouring buildings and performance under different cloud conditions.

5.2. Wind speed and direction

In addition to solar radiation, wind is a key natural stimulus to the thermal and airflow behaviour of the DSF. The front, the top and bottom of the DSF cavity are subject to different wind pressures. During windy days, the wind force plays a dominant role in driving airstreams in the DSF thus having a significant influence on the ventilation of the façade cavity [4,16,54].

The analyses of the wind influence on the cavity temperature suggest that on a typical clear day, the temperature inside the cavity can achieve 50 °C higher than outside for the case with null wind speed. However, when the wind speed of 4 m/s was set to the model, the difference of temperature between the cavity and the outside air dropped to around 30 °C [44].

The wind direction has also a great impact on the quantity and direction of airflow through the DSF cavity and the other building openings. Lou et al. [54] and Stec and Paassen [4] explained that high values of pressure coefficients occurred when the DSF was located at the leeward side of the building. Thus, the airflow in the cavity achieved a minimum for the wind direction parallel to the façade but increased for the perpendicular wind direction.

More detailed studies by Gratia and De Herde [55] showed that when the wind was oriented perpendicular away from the face of the DSF (Fig. 7a), the airflows were similar among the floors, with air taken from outside through the user room and discharged into the cavity. In this case, the thermal stack effect was less significant than the wind effect at the upper floors. On the other hand, when

Table 4
Summary of 'site' parameters and key findings.

Parameter	Author/year	Location	Variation	Tool	Type of ventilation	Major findings/Observations
Orientation and solar irradiance	Stec and Paassen [4]/2005	Specified conditions.	Solar incidence (100, 200, 400, 800 and 1200 W/m^2)	Matlab/Simulink	–	• Only the cavity was modelled. • On a sunny day, the temperature in the cavity may exceed the surrounding temperature by more than 16 °C.
	Gratia and De Herde [44]/2007	Uccle, Belgium.	Clear, mean and cloudy sky conditions West and east orientations	TAS (BES)	–	• On sunny days the temperatures in the cavity for a south facing DSF exceeded the surrounding temperature by around 20 °C. However, under cloudy sky conditions, the maximum temperature difference compared to the outside temperature was 10 °C.
	Kim et al. [53]/2009	South Korea (winter)	East/West facing. Clear and cloud sky conditions	Experimental laboratory measurements + CFD	Naturally ventilated	• The west-facing skin received enough solar radiation to generate ventilation. • The air temperature in the cavity was influenced by irradiance when the sky was clear and partly cloudy, but it did not function effectively under overcast skies since there was not enough radiation to heat up the air in the cavity.
	Haase et al. [41]/2009	Hong Kong, China.	Eight orientations	TRNSYS and TRNFLOW (coupledwith COMIS)	Mechanically ventilated	• The façade design orientation has been identified as having major influence on annual cooling load. • Efficiencies are highest for S, SE, and SW orientation and lowest for N orientation.
	Hamza [54]/2008	Cairo, Egypt.	Four main orientations	IES (BES)	Air conditioned	• Due to the direct solar radiation intensities, the East and West orientations are to be avoided as much as possible, while the North orientation provides the least cooling loads.
Wind speed and orientation	Gratia and De Herde [55]/2004	Uccle, Belgium.	Wind orientation: to the same side and against the DSF facing	TAS (BES)	Naturally ventilated	• If the DSF is on the leeward side, the wind effect which dominates/ • If the double skin is on the windward side, the air flow in the building is only due to the wind effect and the movement is reversed.
	Gratia and De Herde [44]/2007	Uccle, Belgium.	Wind speed: 0, 2 and 4 m/s	TAS (BES)	–	• A difference of 10 °C can be observed in the cavity between the case of a null wind speed and a 4 m/s wind speed, in a summer day by clear sky.
	Lou et al. [54]/2012	Specified conditions.	Incident wind angles	wind-tunnel experiments and numerical modelling	Naturally ventilated cavity	• Inner layer sealed. • Peak values of pressure coefficients occur when the DSF is located at the leeward side of the building
	Stec and Paassen [4]/2005	Specified conditions.	Wind speed (0.5, 2, 6 and 12 m/s) and wind direction (0 to 180°)	Matlab/Simulink and CFD	–	• Only the cavity was modelled. • The air velocity in the cavity is directly proportional to the wind speed; around 4 times lower than the wind speed.

the wind was flowing in the opposite direction (Fig. 7b), air was still extracted into the cavity at the lower floors but in the upper floors, the airflow reversed in direction letting warmer air into the user rooms.

Table 4 presents a summary of the 'site' parameters analysed in this section highlighting the major findings regarding the influence of exterior conditions on DSF performance.

6. Conclusions

This paper has identified and reviewed the parameters that influence the thermal behaviour of buildings with double skin façade (DSF). Relevant studies from the existing body of knowledge that can contribute to the study of DSF in naturally ventilated buildings have been classified and grouped according to the 'façade', 'building' and 'site' parameters, summarising and drawing the findings and conclusions to inform the development and implementation of a potentially low carbon design option. The main deductions applicable to the DSF design for naturally ventilated buildings from this review are:

(1) Narrower cavity is preferred due to the accentuated stack effect and the resulting greater ventilation rate occurring within this space. However, in naturally ventilated buildings the airflow behaviour inside the cavity still needs investigation to account for the effect of different configurations of the openings to the air flow at different floor levels.
(2) Apart from reducing direct solar gains into the user rooms, the heat absorbed by shading device can also increase the air temperature and the stack effect inside the cavity. When placed in the middle of the cavity, the shading device allows smoother air flow on both sides of the device. If placed close to the inner layer, there is the risk of high heat transfer to the user rooms by convection. Regarding the blind angles, horizontal angles may cause obstruction to the air circulation; therefore, vertical positions seem to be more appropriate to reduce hindrance to the airflow in the cavity.
(3) The properties of the glazing materials selected for the DSF layers impact on the heat transfer rates particularly the solar gain. The use of single glazing with high transmittance at the external layer allows for a high heat gain into the cavity, thus increases the buoyancy force for natural ventilation.
(4) The height of the façade cavity is crucial to the DSF performance due to the creation of the buoyancy effect. As a consequence, the shaft-box and multi-storey types seem to be more suitable for naturally ventilated buildings.
(5) A bigger opening area across the cavity reduces the flow resistance thus allows for a greater amount of air flow through the cavity. Thus, maximising the opening area at the top of the DSF would promote higher airflow.
(6) High WWR on the inner layer of the DSF can improve the airflow through the user room; however, the WWR threshold should be identified to avoid excessive solar gain.
(7) The taller the cavity, the greater the buoyancy effect and therefore higher airflow. For naturally ventilated buildings there are chances that the DSF will be enough to promote the natural ventilation needed in the lowest floors, but mechanical systems may be required on the upper floors unless the cavity is extended beyond the roof.
(8) For naturally ventilated buildings located in the north hemisphere, the south facing facade (with 45° variations) seems to be the most effective orientation in capturing the solar gain needed to facilitate the natural ventilation in buildings with DSF.
(9) The wind speed may counteract the influence of the buoyancy effect within the DSF. When applied in naturally ventilated buildings, the DSF tends to perform better if the wind direction is perpendicular and away from the façade.

Studies on DSF in the last decade have been notably extended to a wider range of climate from cool continental to Mediterranean, hot and arid regions. There has been significant progress in terms of the evaluation methods in particular the advances in computational fluid dynamics (CFD) analysis tools, which enable greater understanding of the complex behaviour of the DSF and its interaction with the building without resorting to expensive experiments. The study of DSF on naturally ventilated buildings can be considered still at its infancy as this review highlighted most studies are bared on air-conditioned models. Although naturally ventilated buildings with DSF has great potential to create a thermally comfortable environment even in warm and tropical climates, further research to adapt and evaluate the design from the existing studies identified is needed. In many cases it is unlikely to attain total natural ventilation all year round, a mixed-mode system which alternate between mechanical and natural ventilation, or DSF systems only fulfilling the need for part of the building should be considered. Furthermore, many of the studies have focused on the DSF cavity as an 'isolated' structure and often treated as a local thermal feature without taking into account its influence on the user space. Therefore, holistic investigations of DSF in naturally ventilated buildings fully integrated with the operation and occupation profiles should be further pursued.

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